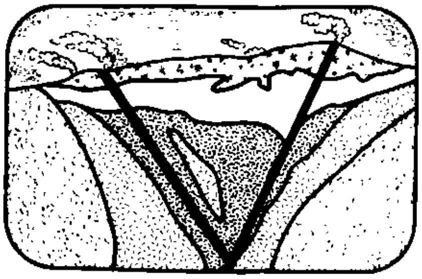

Ore Deposits #9. Disseminated Gold Deposits

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Introduction

Disseminated gold deposits have been attractive exploration targets since the early 1960's when the Carlin deposit in northeastern Nevada was discovered. Before that time, such deposits were known, however, they were considered to be too low grade or too small to be mined profitably. The low gold price and the lack of technology for recovering fine-grained gold from low-grade materials contributed to the unattractiveness of these deposits. However, locally small-scale mining did occur from veins and disseminations where gold became concentrated enough to warrant such activity. In fact, certain disseminated gold deposits have been discovered by reinvestigating historically active lode districts.

For the purpose of this paper, disseminated gold deposits are defined as those deposits originating from hydrothermal processes which contain economic amounts of gold finely dispersed in host rocks of variable composition where little or no fabric control on mineralization is apparent, at least at the hand specimen scale. Beyond this, the variabilities observed in size, grade, textures, mineral associations, nature and degree of structural control, composition of host rocks, association with igneous rocks, nature and degree of alteration, and other factors are such that it is difficult to define these deposits more specifically. The gold is most commonly sub-microscopic or microscopic but locally may become visible to the naked eye. The deposits occur in rocks of all ages, however, the mineralization usually can be related to some Tertiary event.

The variabilities observed make it difficult to develop a general model that can be applied to all deposits. In addition, because of the fine-grained nature of the gold and associated mineralization and the difficulties in recognizing distinctive hydrothermal features such as wallrock alteration, these deposits are difficult to study both in the field and laboratory. However, there are a number of features common to many of these deposits that must be considered in their genesis: (1) the common occurrence of silicification, expressed as jasperoids in most of the sedimentary rock-hosted deposits; (2) the close association between gold and pyrite in primary ores; (3) the anomalously low abundance of common base metals such as copper, lead and zinc; and (4) the occurrence of significant amounts of arsenic, antimony, mercury and thallium in the ores. These factors will be incorporated into the model discussed below along with other characteristics commonly thought of as typical for the deposits, such as the association with carbonaceous material. As will become clear, the latter is not a universal occurrence but is limited to certain sedimentary rock-host deposits.

Before developing a genetic model for disseminated gold deposits, it is necessary to review the characteristics exhibited by these deposits. In this review, emphasis will be placed on the deposits located in the western United States. Specific deposits will be used in the discussion because of their unique or outstanding characteristics which are important in developing a genetic model, availability of literature, and familiarity to the author.

Distribution and Size

Figure 1 shows the location of selected disseminated gold deposits in the western United States. These deposits are listed in Table 1 along with the estimated reserves and grade. Other important deposits are known; however, they are relatively recent discoveries and the available information on these deposits is limited. However, including them here would not seriously affect, either in a positive or negative way, the genetic model.

Host Rocks

Commonly, the host rocks for hydrothermal deposits are considered important in the ore-forming process because they serve as chemical sinks for material dissolved in the solutions. Evidence that exchanges of material occur between rocks and solutions lay in the occurrence of wallrock alteration envelopes around hydrothermal veins. However, the variety in the composition of the host rocks for disseminated gold deposits precludes these having a unique genetic role in the precipitation of the gold. The host rocks for most of these deposits range from early Paleozoic sedimentary units to late Tertiary volcanic rocks.

At the Carlin deposit (Figure 1) most of the gold mineralization occurs in the upper 250 m of the Silurian to Devonian Roberts Mountains Formation. In the mine area, this formation consists of 550-600 m of dark grey thin-bedded laminated silty calcareous dolomite and limestone. Ore occurs as replacements of carbonate minerals, primarily calcite, in the thin-bedded argillaceous arenaceous dolomitic units, whereas peloidal wackestones within the same stratigraphic horizon appear unfavorable for mineralization (Radtke *et al.*, 1980). The main ore host at Jerritt Canyon is a middle unit of the Ordovician to Silurian Hanson Creek Formation (Birak and Hawkins, 1984). This favourable interval consists of more than 90 m of alternating carbonaceous micritic limestone beds and laminated carbonaceous dolomitic limestone beds. Gold mineralization favours the more permeable laminated units. Chert lenses, less than 10 cm long and 2 cm thick, occur sporadically in the lower parts of this unit (Birak and Hawkins, 1984). At Jerritt Canyon mineralization also occurs in the lower part of the Roberts Mountains Formation which overlies the Hanson Creek Formation.

At the Getchell deposit (Figure 1), the main ore hosts are limestone units within the Cambrian Preble Formation, which consists of intercalated thin arenaceous limestone and limey carbonaceous shale beds (Berger, 1980). At the Pinson Mine, about eight kilometres south of the Getchell deposit, gold mineralization is hosted by the Cambrian to Ordovician Comus Formation which directly overlies the Preble. The former unit consists of thin-bedded carbonate and shale which are locally rhythmically interbedded and lam-

Table 1 *Size and grade for selected disseminated gold deposits of Nevada and Utah.*

Deposit	Size* *(Millions of Tons)*	Grade *(oz/ton)*	Source
Alligator Ridge	5.0	0.12	Klessig, 1984b
Battle Mountain			Blake *et al.*, 1984
Minnie-Tomboy	3.9	0.09	
Fortitude	16.0	0.15	
Borealis	2.5	0.08	Wilkins, 1984
Carlin	22.0	0.30	Wilkins, 1984
Getchell	4.4	0.28	Wilkins, 1984
Jerritt Canyon	11.9	0.22	Wilkins, 1984
Mercur	10.1	0.15	Wilkins, 1984
Northumberland	8.0	0.08	Wilkins, 1984
Pinson	3.2	0.16	Kretschmer, 1983
Round Mountain	200.0	0.05	Mills, 1984

*Calculated from historical production and estimated reserves.

inated (Kretschmer, 1984). Carbonate units also host disseminated gold at the Mercur Mine in the southern Oquirrh Mountains of Utah (Kornze *et al.*, 1984). Here the mineralization occurs in the Mercur Mine series within the upper half of the Lower Great Blue Formation of Mississippian age. This series consists of interbedded lime wackestones, packstones, micritic limestones, mudstones, grainstones, fine-grained sandstones and chert. Most of the gold occurs in the Mercur bed which consists of fossiliferous mudstones and grainstones.

At the Alligator Ridge deposit, 110 km northwest of Ely, Nevada (Figure 1), the most important ore host is the lower 100 m section of the 135 m thick Mississippian Pilot Shale. This formation consists of interbedded thin-bedded calcareous, carbonaceous siltstones and claystones. The ore horizon is dominated by dark grey to greyish-black siltstones with local thin lenses of limestone. This lower silty zone is separated from the more clay-rich upper beds by a discontinuous zone of interbedded dark grey, lenticular cherts and light-colored clays (Klessig, 1984a, b). At Copper Canyon, Nevada, gold deposits are hosted by siliceous and calcareous conglomerates in the basal 30 m of the lower member of the Middle Pennsylvanian Battle Formation. The conglomerate consists of sub-angular to sub-rounded clasts of chert, quartzite and rare limestone up to nearly 70 cm in diameter. The matrix originally consisted of calcareous medium-grained sandstone, however, metamorphism has resulted in the formation of tremolite (Blake and Kretschmer, 1983; Blake *et al.*, 1984).

Disseminated gold deposits are hosted by volcanic rocks as well as sedimentary units. At Round Mountain, Nevada (Figure 1) substantial amounts of gold occur in Miocene, intracaldera, poorly- to densely-welded rhyolite tuff (Mills, 1982, 1984). Disseminated gold occurs in Miocene andesitic volcanic rocks at the Borealis Mine near Hawthorne, Nevada (Reid, 1984). Many more occurrences contain gold hosted by volcanic units, however, most show a strong structural control and therefore have not been considered disseminated deposits. In terms of the geochemical processes responsible for mineralization there may be little difference between the typical vein and disseminated deposits.

Structural Control

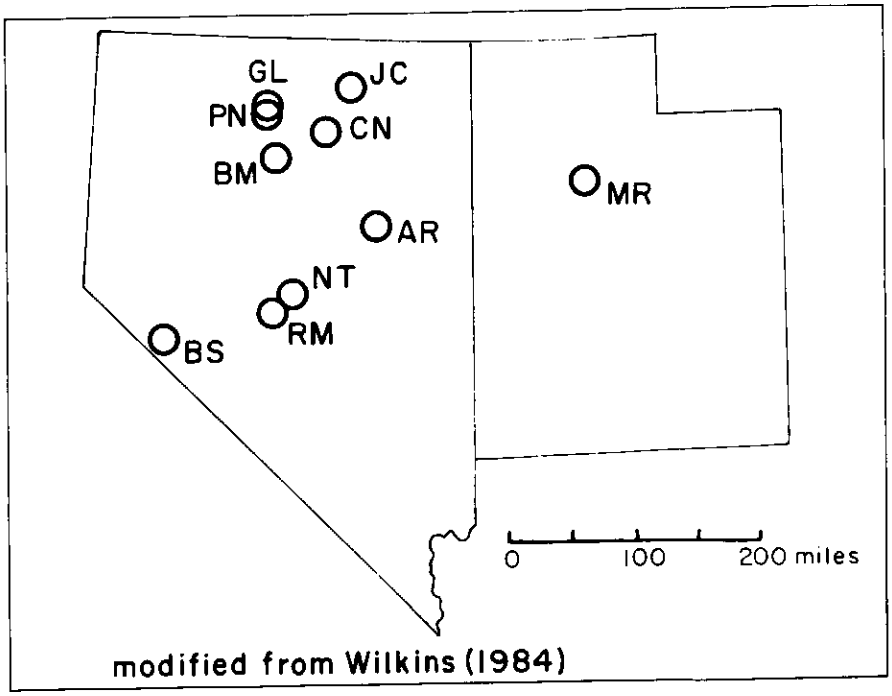
The structural control of disseminated gold deposits can be considered on both regional and local scales. Both are important because of the necessity to recognize features responsible for focussing geological processes which result in economic concentrations of gold, and also the need for plumbing systems to transmit the mineralizing solutions. Yet, there is no structural feature or features which appear to be unique to disseminated deposits. Regional structures may play the role of localizing igneous activity that supplies the energy to drive the hydrothermal system as well as the stress required for mechanical ground preparation. Post-mineralization tectonic adjustments along major belts also may be responsible for exposing the deposits to discovery and exploitation.

On a more local scale, ground preparation through fracturing is important to produce not only the permeability necessary for solution migration but also open spaces for mineral precipitation. The formation of a disseminated deposit as opposed to a vein may depend only on the degree and scale at which the mineralizing solutions can penetrate the host rocks, which in turn depends on the nature of fracturing. The two types of occurrences are found together in many districts and deposits, where structures occupied by veins may have served as feeder systems for the disseminated mineralization.

The style of fracturing will be host-rock dependent as well. Argillaceous sedimentary rocks will yield as well as fracture at depth along a few planes in response to directed stresses. In contrast, volcanic rocks emplaced at or near the surface experience brittle failure resulting in many well-developed open fractures. Fracturing may be in response to stresses produced by the igneous activity (caldera collapse, for example) and permeable volcanic breccias are a common result. Therefore, it is not surprising that disseminated deposits are hosted most commonly by sedimentary rocks and vein deposits by volcanic units.

Roberts (1960, 1966) suggested that mining districts in northern Nevada were aligned along northwest-trending belts. Much of his work was done before discovery of the large disseminated gold deposits in this area although minor vein occurrences in proximity to the latter were known. One belt extends for over 100 km from the Getchell and Pinson Mines in the northwest to the Eureka district in the southwest. Bonham (1984) described the Carlin gold belt, a northwest-trending zone containing a number of important disseminated and vein deposits. This belt can be extended southeast along trend to include Alligator Ridge and the deposits around Ely, Nevada. Many of the disseminated gold deposits of this belt are exposed in windows eroded throgh the upper plate of the shallow-dipping Roberts Mountains thrust. This is a major zone of faulting with significant west to east displacement which occurred during the Devonian to Mississippian Antler orogeny. There may be a genetic relationship between the events producing the uplifts in the window areas and the gold mineralization so that occurrence of the deposits in these windows is not fortuitous.

The Mercur deposit lies in a major west-trending belt of igneous and hydrothermal activity which includes the Bingham porphyry copper deposit and the Park City base and precious metal deposits. This belt is the western extension of the Uinta Arch. In all these belts, middle to late Tertiary normal faulting and igneous activity are superimposed on Paleozoic geosynclinal sedimentary sequences and thrust plates with local occurrences of Mesozoic rocks.



modified from Wilkins (1984)

Figure 1 *Selected disseminated gold deposits of Nevada and Utah. AR, Alligator Ridge; BM, Battle Mountain; BS, Borealis; CN, Carlin; GL, Getchell; JC, Jerritt Canyon; MR, Mercur; NT, Northumberland; PN, Pinson; RM, Round Mountain.*

The occurrence of disseminated gold deposits in distinct belts in western Nevada is less clear. Most of these deposits appear to be related to centres of Tertiary volcanic activity, which, in themselves, suggest zones of crustal weakness. Many of these centres developed on basements consisting of metamorphosed late Paleozoic to Mesozoic sedimentary and volcanic assemblages and igneous intrusions.

On a more local scale, even though most of the gold is hosted by sedimentary, and to a lesser extent volcanic, units, the mineralization shows a strong spatial relationship to fractures in all deposits. Most fracture systems show normal displacement and developed during the Tertiary; however, some may have originated during the Mesozoic and experienced later recurrent movement.

At the Carlin deposit, gold mineralization occurs in the Lynn window in the rocks constituting the lower plate of the Roberts Mountains thrust. Ore occurs in and adjacent to high-angle normal faults of variable strikes and up to a few hundred metres of displacement. This normal faulting had the result of producing extensive areas of shattered rock in the upper part of the Roberts Mountains Formation just below the thrust fault. The normal faults are interpreted as the conduits which fed hydrothermal solutions to the structurally-prepared host rock (Radtke *et al.*, 1980). Particularly favourable structural traps may have been produced by a combination of the movements along the Roberts Mountains thrust and the intersecting normal faults. Locally, mineralization also occurs in the hanging wall of the thrust. A similar structural framework occurs at the Jerritt Canyon deposit although the principal host rocks are different (Birak and Hawkins, 1984).

At the Getchell and Pinson deposits structural control of gold mineralization is much more pronounced. The major structural features in this area are a series of anastomosing high-angle normal faults which form the eastern margin of the Osgood Mountain block. Ore occurs in breccias and gouge along strands of this major fault zone; individual ore widths range up to 70 m (Berger, 1980; Kretschmer, 1984). At Battle Mountain a series of northwest-trending, northeast-dipping mineralized normal faults served as channels for the solutions to penetrate the adjacent conglomerates (Blake and Kretschmer, 1983; Blake *et al.*, 1984).

At the Alligator Ridge deposit the relationship of mineralization to structure is less clear. The rocks in the area have been folded into a series of gentle north-trending folds and subsequently cut by a series of high-angle normal faults. Mineralization is post-normal faulting, however, the spatial and genetic relationships of ore to fractures have not been clearly defined. Klessig (1984a, b) states that mineralizing solutions migrated upward along unspecified conduits and believes that gold deposition is relatively young in age because of the existence of geothermal waters in the area.

Structural control of gold deposits in Tertiary volcanic centres is usually relatively easy to discern. At Round Mountain the mineralization is localized in the Jefferson Caldera in the southern Toquima Range. This caldera is one of four recognized in the area and developed in response to the eruption of large volumes of rhyolitic and rhyodacitic tuffs on a basement of Paleozoic metasedimentary and Cretaceous plutonic rocks (Mills, 1982, 1984). Mineralization appears to be localized along a segment of the structural margin of the caldera where late resurgence of igneous activity occurred. A major northwest-trending shear zone and associated dilatant fractures are overprinted by a system of radial and concentric fractures associated with a central breccia. Vein, stockwork and disseminated mineralization appear to be associated with these zones of intense fracturing. At Borealis such structural control has not been as clearly defined. According to Reid (1984), ore occurs in a breccia adjacent to a partially mineralized northeast-trending fault zone.

Association With Igneous Activity

Igneous activity and its products may serve as sources of metals, transporting solutions and/or heat to drive the hydrothermal systems. The fracture systems required for the migration of the transporting solutions also may be a product of such activity. Magmas are important sources of all three components in some mineralizing systems such as porphyry copper deposits. However, epithermal precious metal mineralizing systems, of which disseminated gold deposits represent a subgroup, appear to be dominated by heated meteoric water (Taylor, 1979; Radtke *et al.*, 1980). Under these circumstances metals must be derived from any material through which the solutions may pass, including the source of the latter, the host rocks, or emplaced igneous material. Alternatively, the latter may supply only the heat to drive the mineralizing system.

All disseminated gold deposits have some plutonic or volcanic rocks occurring in their vicinity, however, the genetic connection between the two has been a matter of significant debate. Deposits hosted by volcanic rocks are usually genetically related to their hosts even though the volcanic history may be quite complex and gold deposition may occur a significant time after emplacement of the hosts.

The genetic importance of igneous rocks in the sedimentary rock-hosted deposits is much less clear. There appears to be no unique association which sets these systems apart from typical metalliferous hydrothermal deposits. On the contrary, these deposits occur in a number of different types of igneous environments with a variety of compositions. The gold deposits at Battle Mountain and Mercur occur in the peripheral zone of major porphyry systems, although the latter deposit lies 20 km south of the centre of the Bingham district and may not be directly related to the copper deposits. At Mercur, fine-grained porphyritic rhyolite intrudes the host rocks adjacent to the gold deposits, but this rock is only weakly altered and contains no gold and may be post-mineralization (Kornze *et al.*, 1984). At Battle Mountain, the gold deposits lie approximately 1500 m south of the main Copper Canyon copper deposits which are associated with a middle Tertiary granodiorite porphyry intrusion. The disseminated gold mineralization occurs within the metamorphic aureole of the pluton and a dyke of the latter occurs in at least one of the deposits (Blake and Kretschmer, 1983; Blake *et al.*, 1984).

At Getchell and Pinson Mines the host Paleozoic sedimentary rocks have been intruded by large masses of Cretaceous granodiorite (Berger, 1980; Kretschmer, 1984). At both deposits portions of the main pluton and cross-cutting dykes are variably altered to sericite, chlorite and clay. At Getchell, alteration appears to be strongest in the vicinity of the ore. Both plutons are surrounded by contact metamorphic aureoles and the gold deposits lie within these zones. Based on spatial relationships and age determinations on alteration minerals Silberman *et al.* (1974) concluded that gold mineralization was Cretaceous in age. However, Berger (1980) reported a major Miocene thermal event in the area based on fission-track studies on apatite from an ore zone. At the Pinson deposit argillized and sericitized andesitic or dacitic porphyry dykes containing low amounts of gold near the ore have been reported (Kretschmer, 1984). These dykes are younger than the granodiorite but their absolute age is unknown.

Mesozoic plutonic rocks underlie the regions around both the Carlin and Jerritt Canyon districts. However, they are considered to be older than the gold mineralization even though dykes of this material occupy normal faults at the Carlin deposit (Radtke *et al.*, 1980). These latter dykes are altered and faulted along younger fractures. Tertiary volcanic rocks with an age of 14 Ma are found in the Carlin district, but are not exposed in the mine. Based on overall geologic relationships, this igneous event is considered the heat source responsible for driving the hydrothermal system. Middle Tertiary andesitic and rhyolitic volcanism occurred in the Jerritt Canyon region as well, however, these units are only exposed in the extreme northeastern section of the district (Birak and Hawkins, 1984). Tertiary rhyolite tuffs and basalts occur in the vicinity of the Alligator Ridge deposits and some of these units appear very young, younger than normal faulting. However, the genetic relationship between the volcanic rocks and mineralization is unknown. Klessig (1984a, b) believes the mineralization to be quite young because of the existence of an active geothermal cell in the mine area.

In the western Great Basin most, if not all, precious metal deposits are associated with various volcanic centres (Albers and Kleinhampl, 1970). McKee (1979) reported a detailed study of the relationship of mineral deposits to volcanism and noted that the majority of these deposits were associated with andesitic volcanism. Most of these deposits are strongly structurally controlled and usually classified as bonanza vein-type ores. However, a few, such as Round Mountain and Borealis, contain significant amounts of disseminated mineralization. The volcanic host rocks for these deposits have been described above.

Ore Mineralogy and Petrography

Similarities between the various disseminated deposits begin to appear when studied at the hand specimen or microscopic scale. These observations are important in developing a genetic model that is generally applicable to most of these deposits. The close association of iron sulfides with the gold in primary ores is a key element in the formation of these deposits. The features these deposits have in common will become clearer in the discussion of the various deposits below.

The most detailed studies of ores in sedimentary hosts have been carried out at the Carlin Mine (Radtke *et al.*, 1980). However, the ores from other carbonate-hosted deposits are remarkably similar to those at Carlin. At the latter deposit, the primary ores have been classified into five gradational types based on the relative abundance of various components: (1) normal, (2) siliceous, (3) pyritic, (4) carbonaceous, and (5) arsenical. An important step in the formation of these ores is the removal of up to 50% of the original calcite in the carbonate host. This ground preparation is thought to have been carried out by the hydrothermal solutions early in their evolutionary history and is important in producing the permeability necessary for the penetration of the ore solutions. However, close inspection of the rocks from this and other deposits reveals many small closely-spaced fractures which give a brecciated appearance.

Over half of the ore consists of the normal type where the gold occurs with mercury, antimony and arsenic as surface coatings on, and fracture fillings in, pyrite grains. In all the primary ore types, gold occurs mostly as coatings on the pyrite. As the carbon, silica and arsenic contents increase to produce the carbonaceous, siliceous and arsenical ores respectively, small amounts of gold may be found with these other components. Organic carbon contents in the normal ore are similar to, but slightly higher than those of unmineralized host rock. It increases from about 0.3% in the normal ore to up to 0.9% in the pyritic ore to over 5% in the carbonaceous ore. Carbon occurs as dispersed grains of amorphous material, hydrocarbons and organic material and in small veinlets and seams of hydrocarbons. Pyrite is the most common sulfide, and increases to 5-10% of the primary ore in the pyritic type. Realgar and stibnite occur in minor amounts in all ore types but increase in the carbonaceous and arsenical ores. The latter ores are paragenetically late and contain gold associated with carbonaceous material and in realgar veins as well as with pyrite. Arsenic contents range from 0.5% to over 10%. The arsenical ores contain unusually high amounts of mercury, antimony and thallium in rare sulfides and sulfosalts. The siliceous ore represents a transition between normal ore and jasperoid as the amount of introduced silica increases. In this type small amounts of fine-grained gold may be found included in quartz grains.

Radtke and co-workers (1980) describe both an acid-leached zone and an oxidized zone at Carlin. They attribute the former zone to hypogene acid oxidizing solutions produced by the oxidation of H_2S to sulfuric acid. The H_2S was released from the hydrothermal solutions during boiling at depth at a temperature of approximately 275°C. This represents a significant increase over the 200°C for the deposition of the sulfide stages in which no evidence of boiling was found. In the formation of the leached zone, barite, anhydrite, quartz and kaolinite were formed and dolomite, sulfides and organic carbon were removed. During the boiling episode, the salinities of the solutions increased from approximately 3 weight percent (wt.%) NaCl equivalent to almost 15 wt.%. Carbon dioxide probably was an important component in the vapour phase because calcite veins were formed above the leached zone during this stage. Finally, the ores were oxidized during normal weathering processes upon exposure during erosion.

The primary ores at Jerritt Canyon, Mercur, Getchell and other carbonate-hosted deposits are very similar to those at Carlin. At Jerritt Canyon, gold occurs in carbonaceous and pyritic silty grainstone or calcareous siltstones (Hawkins, 1984). However, the intimate association between gold and pyrite has not been reported. Birak and Hawkins (1984) state that the most reliable mineralogical indicators of gold are realgar and orpiment; the former is the most abundant arsenic mineral found in the ores. These two minerals occur in carbonaceous rocks in veins with or without calcite and as disseminated grains with remobilized carbon along fractures. Minor arsenopyrite has been detected with X-ray diffraction. Other accessory minerals found are cinnabar, stibnite and barite. In their geologic history of the Jerritt Canyon deposits, Birak and Hawkins (1984) imply that a period of oxidation occurred along with argillization after gold deposition and pre-dating the precipitation of stibnite, barite and the arsenides. Finally, the primary ores have been oxidized by supergene solutions, producing a variety of antimony and arsenic oxides.

At the Getchell deposit, gold occurs as submicroscopic grains associated with carbonaceous material, within sulfide grains, and between quartz and clay grains (Berger, 1980). The carbonaceous material is a mixture of amorphous carbon, organic carbon complexes and graphite, and occurs as thin laminae parallel to quartz layers in the bedding. The pyrite is intergrown with the quartz and commonly contains small blebs and rims of arsenopyrite. Visible gold has been reported in association with pyrite, arsenopyrite and carbonaceous material. However, overall there appears to be a closer association of gold with the sulfides and quartz than with the carbonaceous material. Realgar and orpiment are late in the paragenetic sequence and occur interstitial to ore and gangue minerals along fractures, veins and/or bedding planes. They are also enclosed in masses of late-stage remobilized carbonaceous material. Cinnabar, stibnite, minor base metal sulfides, barite and rare sulfosalts have been reported as gangue minerals.

At the Pinson deposit, the ore consists of a dense jasperoid containing gold, iron oxides and scattered remnants of iron sulfides. Gold has been reported as micron-size inclusions in arsenian pyrite (Kretschmer, 1984).

In the unoxidized ore at Mercur, gold occurs with pyrite, realgar, orpiment, marcasite and cinnabar in relative order of abundance (Kornze *et al.*, 1984). Organic carbon occurs as thin irregular veinlets, thin films coating fossil fragments or as disseminated amorphous material. Some carbonaceous material has been remobilized into carbon-rich pods. Even though there is always some organic carbon present with the gold, the converse is not true. Similarly, gold is always accompanied by sulfides but not vice versa. Barite and calcite occur in late stage veins. Kornze and co-workers (1984) recognize a period of late stage oxidation produced by hypogene hydrothermal solutions. This resulted in the destruction of sulfides and carbonaceous material and the formation of iron sulfates and anhydrite, now gypsum. Some supergene oxidation has occurred, however, most is interpreted as being hypogene.

At Alligator Ridge most of the ore is of the oxidized type and consists of gold, specular hematite, jarosite, stibiconite, goethite, quartz, barite, calcite, gypsum, alunite and kaolinite (Klessig, 1984a, b). The unoxidized ore contains gold in carbonaceous material along with stibnite, pyrite, orpiment, realgar and calcite. The oxidized ore is considered to be hypogene hydrothermal in origin.

The gold mineralization at Battle Mountain contrasts with those so far described in that it occurs in the calcareous matrix of a conglomerate unit with no carbonaceous material present and arsenide minerals are not reported. Sulfide minerals present are pyrite, pyrrhotite and minor amounts of sphalerite, galena, marcasite and chalcopyrite. These occur as disseminations and replacements in the tremolite-bearing matrix. Outside the ore zone, pyrite is more abundant than pyrrhotite and total sulfide content is less than two percent. Within the ore zone, pyrrhotite exceeds pyrite and total sulfide contents range from 10% to 50%. Gold is associated with the sulfides in the disseminations, replacements and fracture fillings (Blake and Kretschmer, 1982; Blake *et al.* (1984).

The mineralization hosted by volcanic rocks is quite different in composition from that in sedimentary rocks yet there are some important similarities, notably the association of gold with sulfides in primary ores. At Round Mountain, gold occurs as immiscible blebs in pyrite in both veins and disseminations. In some high-grade veins, free gold occurs in intimate association with quartz and pyrite. Minor accessory minerals also found in the veins are fluorite, realgar, calcite, adularia and alunite (Mills, 1982, 1984). At Borealis the ores have been acid-leached and oxidized, however, evidence for the preoxidation occurrence of pyrite has been reported (Reid, 1984). Acid leaching has resulted in the formation of quartz, barite, jarosite, alunite and various iron oxides.

Alteration

The most important type of alteration which has occurred in disseminated gold deposits is silicification. In the sedimentary rock-hosted deposits, with the exception of Battle Mountain, this has resulted in the extensive replacement of carbonate units by silica and the formation of jasperoid bodies. These jasperoids are structurally controlled and sometimes change into zones of quartz veining at depth. The existence of jasperoids is a very good indication that gold mineralization is present, however, they vary in gold content from being quite barren to containing several ounces per ton. Because of their resistance to weathering the jasperoids often form ridges, and as such, have served as very good guides to ore. At Jerritt Canyon, approximately 40% of the rocks in the deposit are jasperoids but only 10% represent ore-grade material (Birak and Hawkins, 1984). The deposits in volcanic rocks also exhibit extensive silicification. Round Mountain contains a zone of intense silicification located centrally and vertically above the mineralized area. Silicification was particularly intense in the tuffaceous sedimentary rocks. However, this alteration was not accompanied by gold or pyrite even though late silica veins in the silicified zone contain these minerals (Mills, 1982, 1984). At Borealis, silicification was intense also where zones in the host andesite were completely converted to a rock consisting of quartz and kaolinite.

Other types of alteration recognized in the disseminated gold deposits are decalcification, argillization and oxidation. The early removal of calcite is recognized as being an important process in the preparation of the host rock for later gold mineralization at Carlin, Mercur, Getchell and Alligator Ridge (Radtke *et al.*, 1980; Berger, 1980; Kornze *et al.*, 1984; Klessig, 1984a, b). Early stages of jasperoid are reported for Jerritt Canyon and Pinson (Birak and Hawkins, 1984; Kretschmer, 1984) and supposedly this required removal of carbonate. This decalcification suggests the early hydrothermal solutions were acid, however, they were pre-ore and may be different in composition than the actual mineralizing solutions. In contrast, the formation of calcite veins occurs in the shallow parts of the mineralizing systems in association with the acid leaching at depth.

There are two periods of argillic alteration which are recognized in many disseminated gold deposits. The first is closely associated with the main periods of mineralization and is represented by the formation of various proportions, but small amounts, of kaolinite and sericite. This argillization is best recognized in impure carbonate hosts, volcanic hosts and igneous bodies within mineralized zones. At Battle Mountain in the conglomerate hosts, this alteration is represented by the replacement of tremolite and other metamorphic minerals by epidote, chlorite and clay minerals (Blake and Kretschmer, 1983; Blake *et al.*, 1984). The second and more important episode of argillic alteration occurs during acid leaching in the shallow portions of the hydrothermal system. The mineralogical changes observed include the destruction of sulfides and organic matter, the removal of dolomite in carbonate hosts, and the formation of kaolinite and various sulfates such as iron sulfates, barite and anhydrite. This type of alteration may be accompanied by the precipitation of large amounts of quartz. Because of the buffering capacity of carbonate, this argillic alteration is developed only locally in limestone and dolomite hosts, and may not be recognized at all. In volcanic environments this argillization may result in the complete destruction of the host rock and the replacement of it with an assemblage of kaolinite and quartz with smaller amounts of alunite and other sulfates.

Oxidation is important in the process of argillic alteration described above. Supergene oxidation is widely recognized in disseminated gold deposits and occurs usually in a zone spatially related to a present or paleoerosion surface. During this process, the sulfides and organic carbon are removed, and a variety of iron, arsenic and/or antimony oxides are formed. Some recrystallization of gold may occur as visible gold becomes more common and its grain size may increase by an order of magnitude or more. Because of the greater permeability along fractures, supergene oxidation may be detected to greater depths along veins. This creates confusion between supergene and hypogene oxidation and has led to significant debate concerning the relative importance of each in the formation of gold deposits.

Based on spatial and geochemical data, hypogene oxidizing solutions have been postulated in the formation of many disseminated gold deposits. Whether or not these solutions actually transported gold, or were superimposed on an earlier depositional event is still debatable. In addition, the oxidizing event may be occurring at one point in the system as gold was deposited elsewhere. The oxidized zone at Carlin has been described already (Radtke *et al.*, 1980). The spatial distribution of oxidized rock at Alligator Ridge suggests that hypogene oxidizing solutions permeated the ore zones at some stage in their development (Klessig, 1984a, b). Hypogene oxidizing solutions are described for Mercur (Kornze et al., 1984) and Jerritt Canyon (Birak and Hawkins, 1984). The mineralogical changes occurring are similar to those for supergene oxidation. However, remnants of sulfide commonly occur within the oxidized zone and the grain size of the gold increases. These facts may lead to the conclusion that the oxidizing episode was superimposed upon an earlier mineralizing event involving more reduced solutions.

The Model

Most of the models proposed for epithermal precious metal deposits have been centered around the bonanza vein-type deposits, with the exception of the model for the Carlin deposit by Radtke and co-workers (1980). In their development of genetic models for epithermal deposits, Buchanan (1981) and Berger (1982) assumed mineralization to have occurred in fossil geothermal areas where the hydrothermal solutions were chemically-evolved, heated ground waters (Taylor, 1979). In addition, Henley and Ellis (1983) discussed the similarities between present-day geothermal systems and epithermal gold deposits, and implied the importance of ground water in the formation of the latter. Buchanan (1981) and Roedder (1984) summarized the compositions of solutions from which gold precipitated in hydrothermal systems, obtaining data from fluid inclusions and natural ore, gangue and alteration mineral assemblages. The temperatures of formation for most epithermal deposits were in the 200-300°C range. Many deposits exhibit evidence that the mineralizing solutions boiled at least in some stage of the deposition of gold. The solutions had salinities averaging around 3 wt.% NaCl equivalent and rarely exceeded 10 wt.%. Available data suggest sodium chloride is the most abundant dissolved component with smaller amounts of calcium and potassium also present. Carbon dioxide may be present in significant quantities in hydrothermal systems responsible for the sedimentary rock-hosted deposits.

The genetic models developed for most epithermal vein-type deposits can be applied only in a general way to the sedimentary rock-hosted disseminated deposits. These models assume a sub-vertical open fracture system along which hot solutions rise and precipitation occurs as a result of some physico-chemical changes occurring in the system. The result is a mineral deposit with a relatively simple and predictable symmetry and consistent zoning around individual fractures or fracture zones. These models also assume that boiling is an important process in the genesis of the deposits and there is no doubt that this is an effective mechanism for gold deposition (Romberger, 1982, 1983, 1984; Drummond and Ohmoto, 1985). However, evidence for boiling in the sedimentary rock-hosted deposits is sparse. Even in the well-studied Carlin deposit, evidence for boiling was found only during the stage of acid leaching (Radtke *et al.*, 1980).

The hydrothermal system must be open to the surface for boiling to occur. Even though much of the mineralization in disseminated deposits is fracture-controlled, portions of the ore are stratigraphically and structurally situated such that open conditions could not have existed locally. Rather than a simple upward flow, solutions probably migrated in a variety of directions, depending on the distribution of hydrologic potentials. The factors influencing the flow of the hydrothermal solutions actually may originate well outside the site of ore deposition; the latter may represent a local geochemical anomaly in a much larger flow regime.

Based on the temperature data so far collected on these deposits, it seems likely that increases in geothermal gradient, either regionally or on a local scale, are the driving force behind solution migration during mineralization. Before this thermal perturbation the ground water and deeper pore fluids were close to a state of hydrologic equilibrium where permeabilities and porosities decreased with depth, depending on the nature of the aquifers (Figure 2a). Under such conditions the deeper pore waters would have a significant residence time, especially in impermeable shales, while the shallower groundwaters experienced reasonable rates of recharge, again, depending on the stratigraphy. The change from a shallow recharging system to a deeper static regime may be gradational with a transitional mixing zone between. Under these conditions, the deeper waters will approach chemical equilibrium with their reservoirs while the shallower waters maintain a certain degree of oxygenation due to recharge from the atmosphere. The pore fluids in the deep zones become more and more reducing, particularly if the reservoir rocks contain significant amounts of sulfides and/or organic carbon. During this chemical evolution these fluids will leach various components from the rocks which are compatible with their developing reduced composition. Thus we have two contrasting ground-water environments, a deep reduced solution overlain by a relatively more oxygenated one.

As the geothermal gradient begins to increase from below, bulges will appear at the interface between the two zones (Figure 2b). These irregularities will develop at sites where the rocks have increased permeabilities, such as along fractures. As more heat is added these plumes of reduced pore fluids expand up along the fractures within the oxidized zone. The shapes of the plumes will be controlled by the distribution of permeabilities, expanding out from the fractures in permeable hosts and narrowing where claystones and other aquitards are encountered (Figure 2c). During the rise in the geothermal gradient and the doming of the ground water surface, heating of the deep pore fluids may result in the migration of volatile components such as CO_2 and H_2S upward into the oxygenated ground-water environment. These components will dissolve and the H_2S will oxidize to produce locally acid solutions. These acid waters may be responsible for local solution of carbonate rocks, an important process in the preparation of the host rocks for subsequent gold mineralization. As the reduced pore fluids continue to migrate, the source rocks must be recharged from below, laterally or above, depending on overall hydrologic regime. Migration of the solutions will be slow at first because the geothermal gradient will be increasing from below rocks of low permeability. Recharge may be slow enough to maintain the overall zoning in the composition of the waters. The rate at which the system develops may play an important role in controlling the size and grade of the disseminated deposits; the slower the development, the more gold is transported out of the reduced zone up into the host rocks. Eventually, the convection cell will develop to the point that mixing occurs between zones, recharge of the source rocks breaks down because the ground waters will not migrate up the thermal gradient and/or overwhelming recharge from the oxidized zone will cut off the source at depth (Figure 2d). The latter will result in the superposition of an oxidized assemblage on an earlier reduced one. This entire process may wax and wane with the growth and decline of the geothermal gradient, and over the hundreds of thousands or even millions of years that these deposits have to develop, several episodes of gold remobilization and deposition may occur. At the same time tectonic activity, erosion, sedimentation and/or volcanic activity can change the structural frame-work, further complicating the mineralizing history. This model can be applied equally as well to the volcanic environment except the geothermal gradient would be steeper, events would occur over a shorter period of time, the host rocks would be fractured and brecciated volcanic units, and shallow ground water would be much more involved.

It is now necessary to build into this model the unique geochemical nature of the deposits. The common occurrence of silicification is due primarily to the transporting solutions moving down significant thermal gradients. In most solutions the primary factor controlling the solubility of silica is temperature, particularly at the depths and pressures typical of disseminated gold mineralization. Quartz has a prograde solubility so that cooling is an adequate mechanism for deposition. In contrast, calcium carbonate exhibits a retrograde solubility. The combination of these two contrasting chemistries will result in the replacement of limestone by quartz by a cooling solution saturated with silica, or the formation of jasperoid. Cooling may be caused by loss of heat to the wall-rocks or mixing with cooler ground waters. Silica is one of the easist of the rock-forming components to dissolve in a hydrothermal system, and the deposition of quartz or other forms of silica is not unusual to such environments. The presence of jasperoid or quartz veins need not be acompanied by gold or other metals. Their presence does, however, indicate that the hydrothermal processes necessary for the formation of gold deposits had occurred.

The association of gold with elements such as mercury, arsenic, antimony and thallium and the lack of occurrence of the common base metals such as copper, lead and zinc can both be explained by processes taking place at the source. As the deep pore solutions approach chemical equilibrium with their enclosing rocks, they become more and more reducing, particularly if the aquifers contain significant amounts of organic carbon and sulfide. As these solutions leach the rocks, the only components that will go into solution are those that are soluble at very low oxygen activities in the presence of sulfur. Such elements are those that form soluble sulfide complexes such as gold, mercury, arsenic and perhaps antimony and thallium. Barium may be included here because it does not form an insoluble sulfide but is insoluble as a sulfate. Thus, barium will be mobile in the reducing environment and immobile under oxidizing conditions, as its presence in the oxidized zones as barite indicates. In contrast, those elements which form insoluble sulfides and are soluble as chloride complexes in an oxidizing environment such as the base metals will not go into solution in the reduced pore fluids. Thus a separation of the gold "group" elements from base metals will occur at the source. Any base metals that are dissolved will become more soluble as the solutions penetrate a more oxidized environment and, therefore, will not be deposited. In contrast, Romberger (1982, 1983,

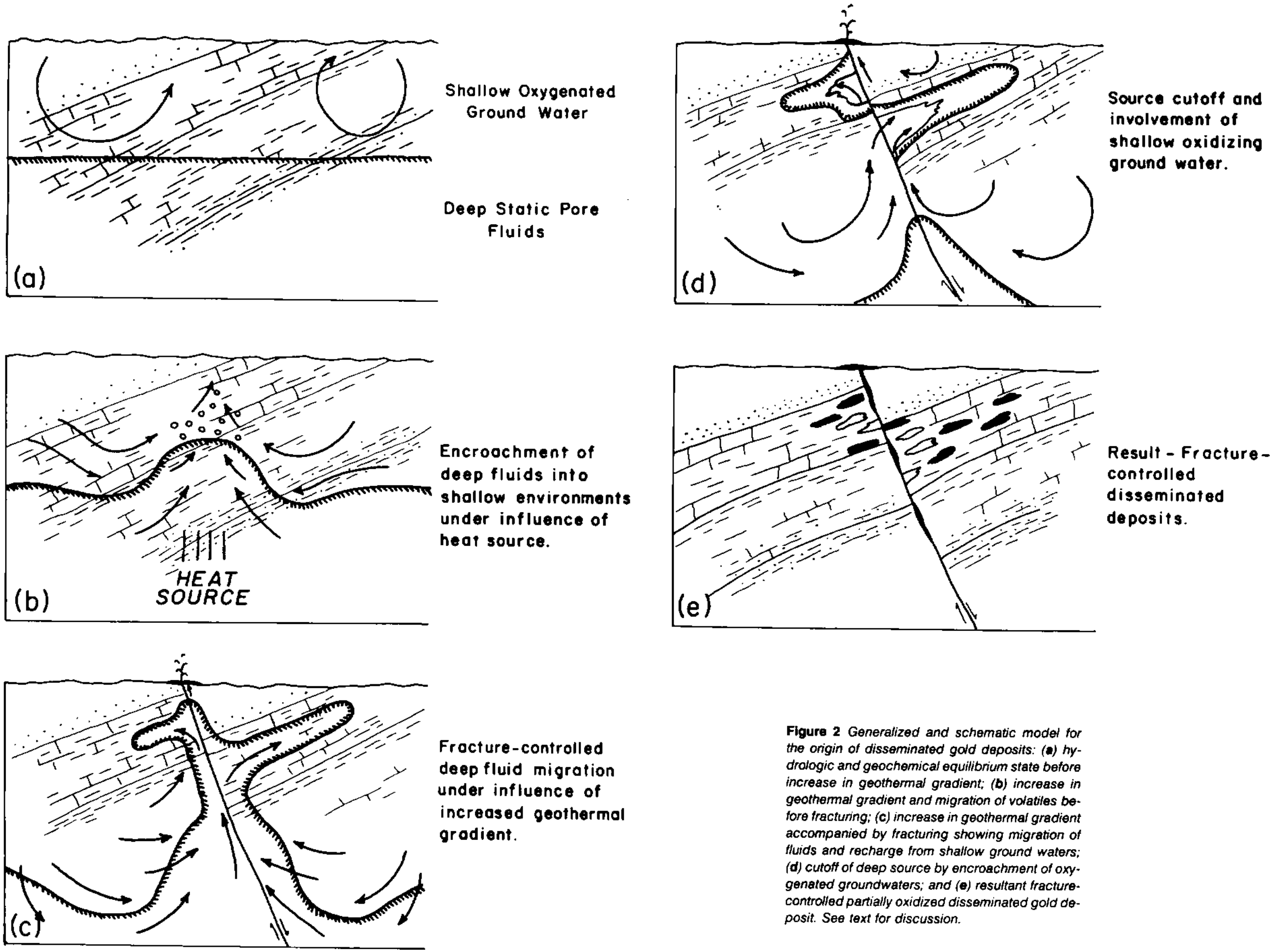


Figure 2 *Generalized and schematic model for the origin of disseminated gold deposits: (**a**) hydrologic and geochemical equilibrium state before increase in geothermal gradient; (**b**) increase in geothermal gradient and migration of volatiles before fracturing; (**c**) increase in geothermal gradient accompanied by fracturing showing migration of fluids and recharge from shallow ground waters; (**d**) cutoff of deep source by encroachment of oxygenated groundwaters; and (**e**) resultant fracture-controlled partially oxidized disseminated gold deposit. See text for discussion.*

1984) has shown that oxidation is a very efficient mechanism for the deposition of gold transported as bisulfide complexes (Figure 3) and would apply equally as well to the other metals in solution as one sort of sulfide complex. In addition, the same mechanism would result in the deposition of barite as the activity of sulfate increased during oxidation of sulfide. Figure 3 shows the solubility of gold as a bisulfide complex in the heavy line as a function of the activity of oxygen, increasing to the right, for a solution at 250°C and pH of 5. Neutral pH at this temperature is 5.5, and the relationships will not change significantly by assuming a higher pH. The other assumed solution parameters are given. Also shown are the ranges of oxidation state over which pyrrhotite (Po), pyrite, and iron oxides or chlorite would be stable. The field of stability of graphite is shown as the hatchured area, as are oxidation conditions under which methane, carbon dioxide, reduced sulfide (H_2S) and sulfate would predominate. The diagram shows that once a solution passes from the sulfide field to that of sulfate the solubility of the gold bisulfide complex decreases quite rapidly. Therefore, gold would be deposited as a result of oxidation of solutions saturated with this metal. The diagram shows the path (labelled NZ) a solution would take which was originally in equilibrium with the mineral pair pyrrhotite and pyrite and had a gold content of 0.004 ppb (Weissberg *et al.*, 1979). This solution would be undersaturated with respect to gold originally, however, upon oxidation its composition would pierce the solubility surface and gold would precipitate, as shown. The solubility of gold as the chloride complex is shown for comparison as the heavy dashed line. It is interesting to note that the oxidation of a similar solution containing methane would result in the deposition of carbon.

Romberger (1984) also argued that most hydrothermal solutions in equilibrium with pyrite never reach saturation with respect to gold and the latter co-precipitates with sulfides. He based his arguments on the high solubility of gold in bisulfide solutions (Seward, 1973) and the intimate association between gold and pyrite in most primary ores (Figure 3). The gold ends up either in solid solution in the pyrite or other sulfides or as blebs in or coatings on the grains. As hydrothermal activity proceeds, recrystallization will result in the gold forming discrete grains but still in association with the sulfides. Later oxidation may remove the sulfides, converting them to oxides, however, the gold will remain because of its limited solubility in oxidized solutions.

Summary

In summary, using the physical, hydrologic and geochemical model proposed above it is possible to explain both the structural variations and geochemical similarities exhibited by these deposits. Minor unexplained features do occur, and subsequent major geologic events may mask the original environment. In addition, the behavior of trace metals is presently only conjectural and needs to be strengthened by more work. However, the model is strong enough to withstand a few unknowns. It is believed that further studies on these deposits and the contained material will serve to strengthen it even more.

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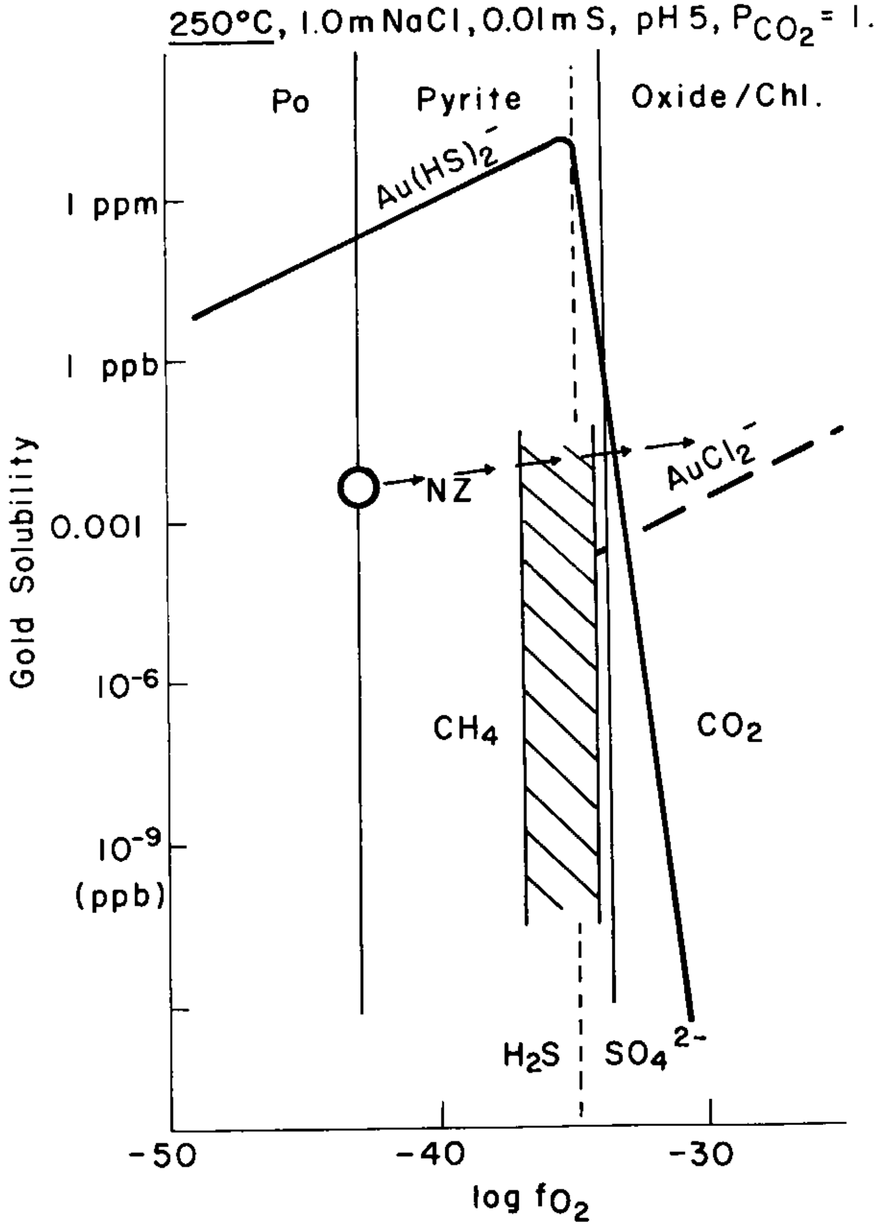

Figure 3 *Calculated gold solubility versus oxygen activity at 250°C, pH 5, and CO_2 (CH_4) pressure of 1 atm showing the solution path during oxidation of a solution starting with 0.004 ppb Au buffered by the mineral pair pyrite-pyrrhotite. See text for discussion.*

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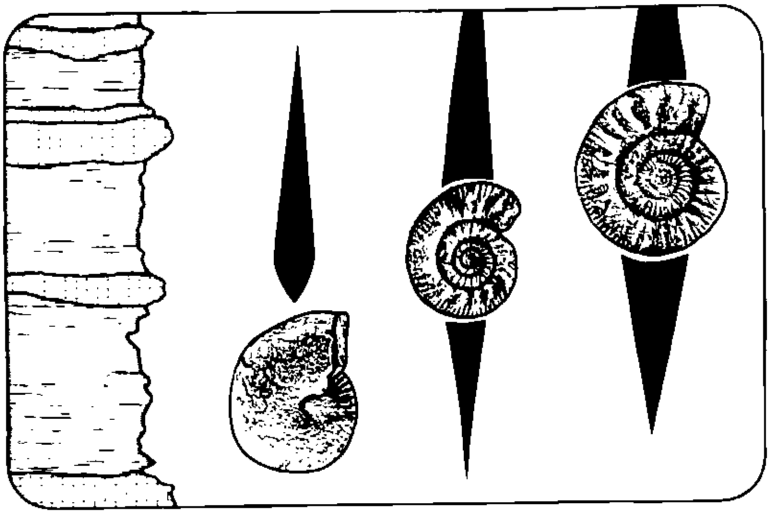

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